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A SYSTEMATIC APPROACH TO ERROR FREE TELEMETRY

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June 2017

TECHNICAL INFORMATION MEMORANDUM

412TH TEST WING
EDWARDS AIR FORCE BASE, CALIFORNIA
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14. ABSTRACT

This technical information memorandum documents flight test results of a telemetry experiment conducted at Yuma Proving Grounds with the goal of providing error-free telemetry data from a helicopter utilizing various multipath mitigation techniques.

15. SUBJECT TERMS

AMT (Aeronautical Mobile Telemetry), frequency diversity, spatial diversity, DQM (data quality metric), DQE (data quality encapsulation), BSS (best source selection)

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INTRODUCTION

The airborne telemetry channel between the test article and ground receiving station introduces impairments that distort the received signal. These impairments, mainly in the form of multipath, can be severe enough to make correct decisions on the received data nearly impossible. Through various developments over the years, there are technologies available today to mitigate some if not all of these impairments. But to date, never have the technologies been implemented together in a coherent fashion that exploited the benefits of each.

Yuma Proving Grounds offered a small test team of industry and Government telemetry experts the opportunity to not only perform real-time experimentation but also demonstrate that with an understanding of the problem coupled with forward thinking, a telemetry system could be designed, implemented, and tested that provided what every Range customer wants: error-free telemetry.

BACKGROUND

Over the last several years advances in aeronautical telemetry has supplied the telemetry engineer with tools to mitigate most if not all transmission channel impairments. Technology has been specifically developed for telemetry in the form of Space-Time Coding, Low-Density Parity Check forward error correction (which leveraged existing correction codes for deep-space communication links), and bandwidth efficient constant envelope modulation schemes SOQPSK-TG and ARTM CPM. These developed technologies have all been laboratory and flight tested, standardized [1], and productized and are now finding their way onto test ranges. These tools along with the tried and true methods of frequency and spatial diversity are now readily available to be implemented during the telemetry link design process.

Space-Time Coding (STC) [3], a form of transmit diversity, has been shown through theoretical studies [7] and flight testing developmental hardware to mitigate the co-channel interference problem created by utilizing two antennas to transmit the same telemetry signal [8]. This has also been referred to as the “two antenna problem” and is a self-inflicted source of co-channel telemetry signal distortion. During a flight test mission, telemetry signal shadowing caused by the airframe under certain airplane-to-ground station geometries can exist should only one transmit antenna be used. Conversely, using two transmit antennas mitigates shadowing but introduces another issue, a distorted composite transmit antenna pattern with nulls as deep as 20dB. The STC is designed to mitigate this distortion by space-time coding the baseband signal into two RF signals, S0 and S1 at the same center frequency and transmit each using two antennas.

Forward error correction (FEC) is used to enhance transmitted data reliability by introducing redundant data (parity) prior to transmission. Forward error correction has been around for many years and comes in many different forms. The correction code implemented within the telemetry community is Low-Density Parity Check (LDPC) [2] which is a “block” code. A block of information bits have parity added to them, this parity aids in the correction of errors in the transmitted information bits once they are received at the ground station. LDPC is a very powerful correction code offering gains in link margin as much as 9dB.

Spatial and frequency diversity techniques are not new to the flight test community or to the wireless communication community in general. Both are mitigation techniques to fight the effects of multipath on the transmitted signal given one general concept, multipath will not occur at the same time with the same severity on two or more diverse telemetry signals. These multiple diverse signals are created one of two ways, either in frequency or in space. Frequency diversity is created on the test article; the same data stream is transmitted on two (or more) separate frequencies, for example F1 and F2. On the ground station both frequencies are received and a choice is made, either by a combiner (operating in the frequency domain) or best source selector (operating in the time domain), as to the best signal to use. Spatial diversity uses several ground stations placed around the test range(s) to receive the signal(s), route these demodulated signals to a main control center, then make a decision on the best signal to use. A combination of the two techniques can also be used to provide a greater level of multipath immunity.

Until recently, the key technology required to correctly implement diversity techniques did not exist, <u>"smart" diversity selection</u>. The testing at YPG was the first actual flight test that implemented a new technique of assessing the quality of each link, passing along that information with each signal source, and then using that information to choose the best source.

With all these tools available, can they be put to practice in a cohesive manner with the goal of not only increasing the robustness of the telemetry link but also provide the test engineer with error-free data? Answering this question was the goal of this testing.

TEST OBJECTIVE

The objective of any telemetry link design is to provide the control room user with the best possible data. The testing at YPG provided the opportunity to systematically improve the end data quality through the use of various telemetry link impairment improvement techniques. At each stage of the testing, from a baseline configuration to a system configuration using all of the tools available to improve the link, data quality improvement was assessed so a clear progression path of added link availability could be illustrated.

<u>Diverse Source Selection:</u>

The key enabling technology that allowed the combined use of these mitigation techniques was diversity selection, commonly called Best Source Selection (BSS). Up until recently there was not a robust method to assess link quality, time-align each source, and then choose the best source on a bit-by-bit basis. The key here is not the time alignment or the bit-by-bit selection, but the accurate assessment of individual link quality done at the receive site.

Bit errors are the one defining figure of merit for instantaneous link quality. In order to determine if a bit is in error, the original data must be known. Without this knowledge, the next best assessment is the <u>probability</u> that a bit is in error, commonly refer to as bit error probability (BEP). Based upon testing of their demodulation schemes within their line of telemetry receivers, Quasonix has determined a method for assessing real-time BEP of the received signal [5]. The proposed metric, Data Quality Metric (DQM), uses the theoretical work identifying that voting on each bit with a log-likelihood weighting factor leads to an optimal or "maximum likelihood" decision [6]. This weighting factor is calculated as using equation 1:

$$LikelihoodRatio(LR) = \frac{(BEP)}{(1-BEP)} \quad (1)$$

In a general form, DQM can then be calculated using equation 2 as:

$$DQM = \frac{-log_{10}(LR)}{k}\,(2^n) \quad (2)$$

where: k is the chosen exponent for lowest BEP
n is the number of DQM bits

For the hardware tested at YPG, k=12 and n=16 which results in the DQM values for BEP values between 0.5 and 1e-12 (or 1 bit error in 1,000,000,000,000 bits). These values are listed in table 1.

Table 1 Likelihood Ratio and DQM (k=12, n=16) versus BEP

BEP	LR	DQM
0.5	1.00	0
1E-01	1.11111E-01	5211
1E-02	1.01010E-02	10899
1E-03	1.00100E-03	16382
1E-04	1.00010E-04	21845
1E-05	1.00001E-05	27307
1E-06	1.00000E-06	32768
1E-07	1.00000E-07	38229
1E-08	1.00000E-08	43691
1E-09	1.00000E-09	49152
1E-10	1.00000E-10	54613
1E-11	1.00000E-11	60075
1E-12	1.00000E-12	65535

Given the DQM for each source, the telemetry receiver must now package this information for another box downstream, the Best Source Selector (BSS). The BSS will compare the quality metric of each data stream and select the best stream. The message structure that was used for this testing is shown in Figure 1. The DQM is assigned to a block of data that could range from 128 to 16536 bits, for this testing the block was 4096 (2^{12}) bits long. The structure in Figure 1 is known as Data Quality Encapsulation, or DQE.

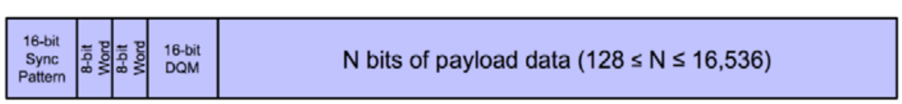

Figure 1 DQE Structure

There now exists a method to assess data quality at the telemetry receiver, DQM, and send this information along with a block of data it applies to, DQE. A BSS can now take in many diverse telemetry streams with DQE, based upon DQM values smartly decide which to choose, and present

the best source to the end user. Given this ability, diversity methods to fight telemetry channel anomalies can now be reliably implemented.

Link Availability:

Because the channel is not strictly noise limited, making an assessment of link quality based solely in terms of a bit error rate is not valid. The metric that best describes how well a telemetry link functions over time, or in this case during a test run, is called Link Availability (LA) as described in [4]. This metric accounts for other sources of link outages other than noise. Link availability, as a percentage, is calculated using equation 3:

$$LA(\%) = \frac{[TotalTime - (SES + PLS)]}{TotalTime} * (100\%) \tag{3}$$

where: *TotalTime* is the time of the test run in seconds

SES is Severely Errored Second defined to be a second where the BER$\geq$1.0e-5

PLS is Pattern Loss Second defined to be a second where synchronization was lost

TEST METHOD

Yuma Proving Grounds supplied the range in which to operate, the test article, flight crew, installation support, three telemetry receive sites, and the infrastructure and manpower required to accomplish four test flights over two days. The test team was charged with the checkout of the transmit system in the helicopter, installation and checkout of the receive and monitoring hardware at each of the receive sites, and system monitoring and data logging during the flight testing. Data reduction was accomplished at the end of each flight ensuring the data captured provided results justifying test progression to the next mitigation technique.

A UH-1 “Huey” was used as the test vehicle. A Space-Time Code enabled transmitter optioned with LDPC forward error correction was installed in the aircraft test rack with one of its two RF outputs connected to the upper antenna and the other RF output to the lower telemetry antenna. An important feature of an STC-enabled transmitter, when not operating in STC mode, is that is can operate as two independent transmitters. This is important for this testing as this capability allowed frequency diversity coupled with a selection of different modulation modes (PCMFM and SOQPSK).

On the ground side, three geographically separated telemetry sites (Site 4, Site 2, CM 4) within the YPG range, see Figure 3, were outfitted with a dual channel telemetry receiver with data logger and a telemetry over IP (TMoIP) capability to allow the received data to be sent to a central location. The central location, Site 4, housed the Best Source Selector and data logger along with all of the equipment necessary to control all of the remote ground station test assets. Figure 2 illustrates this test set-up.

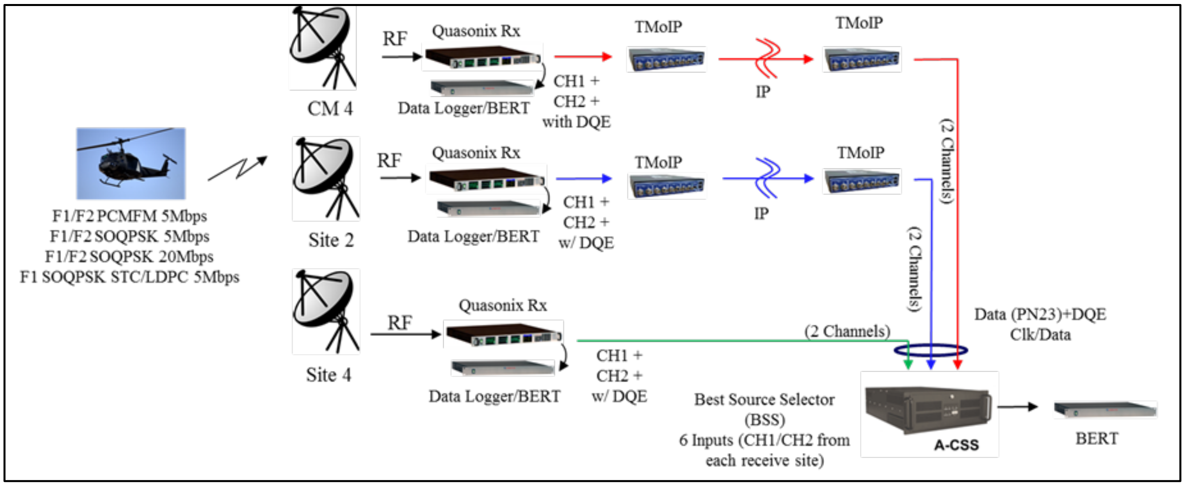

Figure 2 Test Set-Up Block Diagram

A known bit pattern, in this case a pseudo-random bit sequence 2^{23}-1 in length (PRBS23) was used to enable the calculation and determination of link quality improvements in terms of Link Availability for each flight. Table 2 shows the progression of flights starting with determining baseline telemetry link performance and progressing to applying diversity and coding techniques to improve LA. The same flight path was flown for each flight making comparisons of the results between flights valid. The flight paths used were intended to simulate various test routes flown at YPG. See Figures 4 & 5 for the flight paths for each flight.

Table 2 Flight Tests

Flight	**Configuration**
Flight 1 Test 1	PCM/FM F1/F2 5Mbps
Flight 2 Test 1	SOQPSK F1/F2 5Mbps
Flight 3 Test 1	SOQPSK F1/F2 20Mbps
Flight 4 Test 1	SOQPSK-STC/LDPC F1 5Mbps

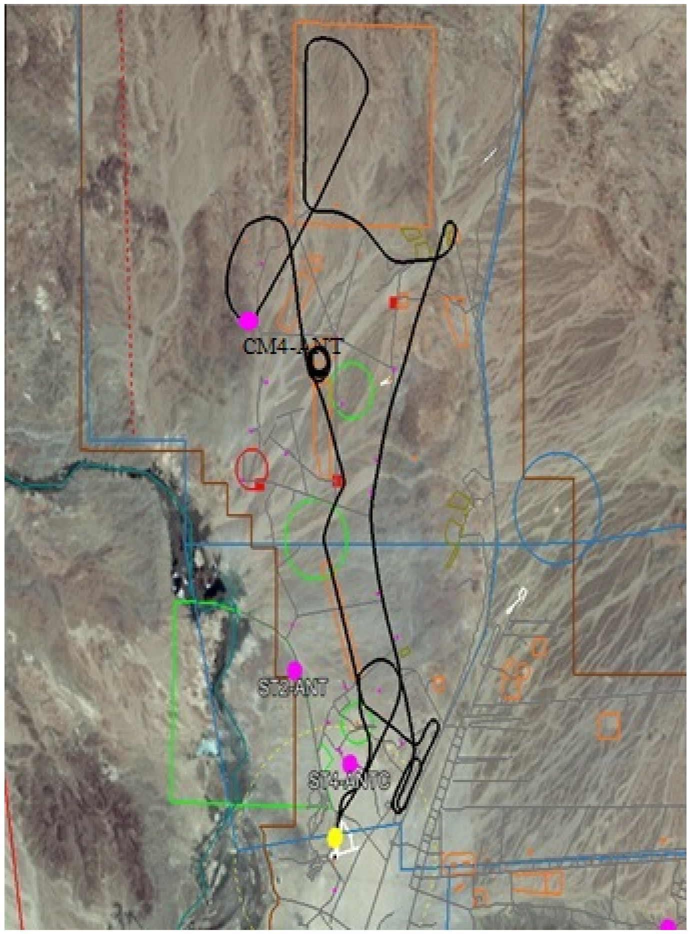

Figure 3 Flight Path at YPG

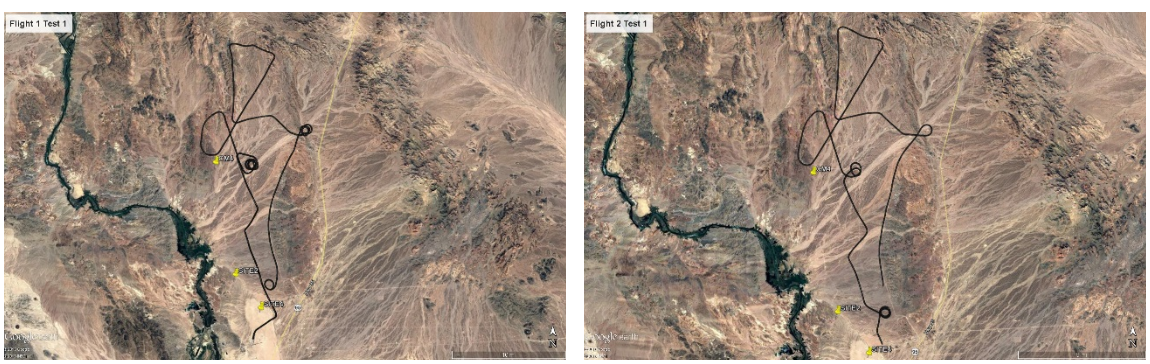

Figure 4 Flight 1 and 2 Test 1 Flight Tracks

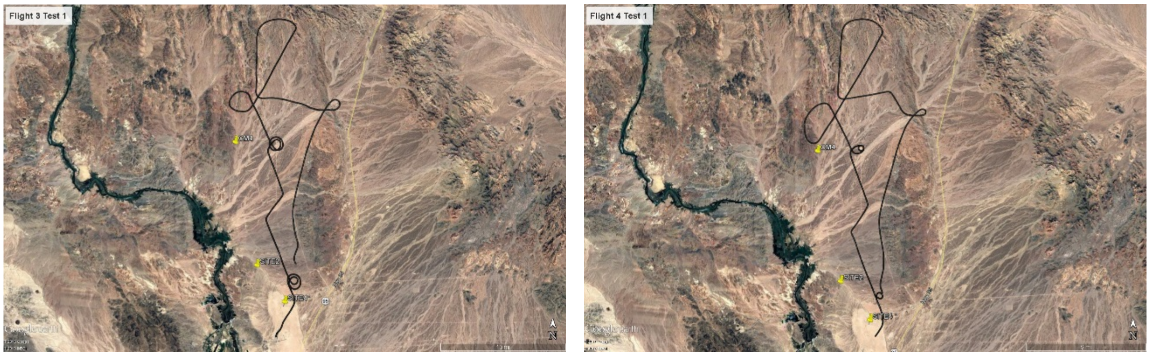

Figure 5 Flight 3 and 4 Test 1 Flight Tracks

TEST RESULTS

Data from each flight was not only viewed real-time at Site 4 but also logged, reduced, and analyzed after each flight. A picture showing where and how the data was captured are shown in Figures 2 and 6. Baseline link performance for PCMFM and SOQPSK modulation schemes at 5Mbps was performed first. Since frequency diversity was one of the mitigating techniques under investigation, baseline link performance was further broken down on a per transmit antenna basis, upper versus lower transmit antenna. Once the baseline was determined, mitigation techniques to better the link performance were incrementally added. Test progression was as follows:

1. Baseline Link Performance – Link Availability on a per modulation and transmit antenna basis.
2. Single Site Frequency Diversity – Link Availability at each receive site utilizing frequency diversity.
3. Frequency Diversity combined with Spatial Diversity – Link Availability using frequency diversity coupled with best source selection of spatially diverse receive sites.
4. Single Site Space-Time Coding coupled with Low Density Parity Check forward error correction – Link Availability at each receiving site on a per receive polarization basis using STC to mitigate the nulling in the composite antenna pattern coupled with LDPC forward error correction.
5. STC/LDPC combined with Spatial Diversity – Link Availability using STC with LDPC coupled with best source selection of spatially diverse receive sites.

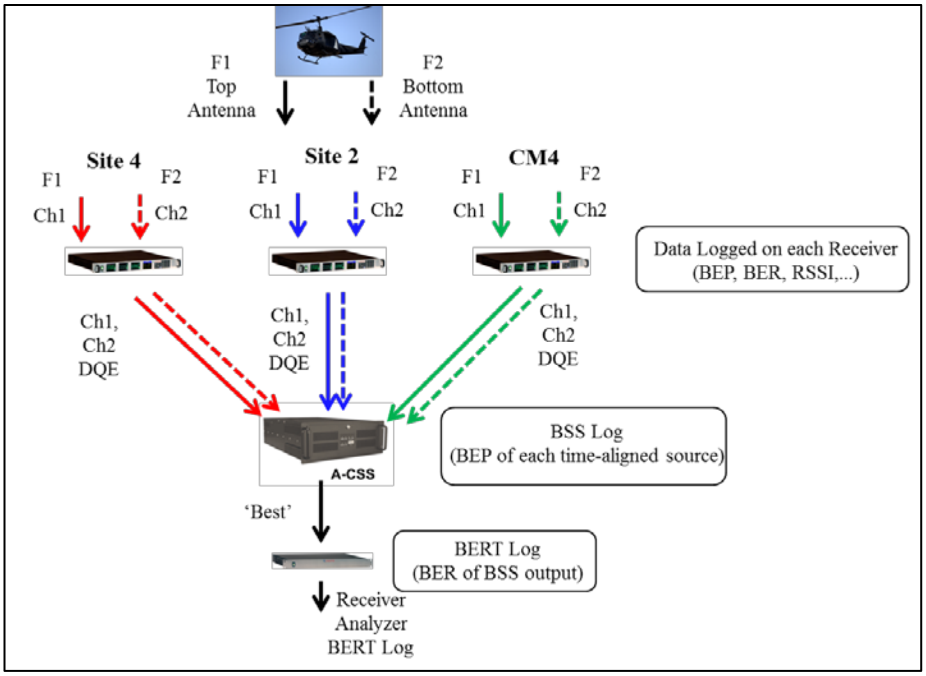

Figure 6 Flight Data Logging

PCMFM Baseline:

On a per receive site basis, table 3 shows the baseline performance of the PCMFM link operating at 5Mbps. Based upon past testing at YPG, these results are typical of PCMFM link performance in a helicopter environment without any mitigation techniques applied. These will be the LA numbers used for comparison purposes for PCMFM. For this test, channel 1 of the telemetry receiver was tuned to the upper antenna frequency (2240.5MHz), channel 2 was tuned to the lower antenna frequency (2260.5MHz) and Link Availability was calculated for both of these signals at each site.

Table 3 PCMFM Baseline Link Availability

	LINK AVAILABILITY					
	Site 4		Site 2		CM4	
Flight	Upper Ant (F1)	Lower Ant (F2)	Upper Ant (F1)	Lower Ant (F2)	Upper Ant (F1)	Lower Ant (F2)
PCMFM 5Mbps (Baseline)	**86.1%**	**93.6%**	**77.0%**	**87.0%**	**83.3%**	**90.1%**

SOQPSK Baseline:

The LA results in table 4 are the baseline performance of the SOQPSK link operating at 5Mbps and 20Mbps at each receive site. These results are new to YPG as they typically use PCMFM modulation to support their testing. The calculated LA numbers for both 5 and 20Mbps will be used as the baseline link performance when assessing link improvement techniques. For this test, channel 1 of the telemetry receiver was tuned to the upper antenna frequency (2240.5MHz), channel 2 was tuned to the lower antenna frequency (2260.5MHz) and Link Availability was calculated for both of these signals at each site.

Table 4 SOQPSK Baseline Link Availability

	LINK AVAILABILITY					
	Site 4		Site 2		CM4	
Flight	Upper Ant (F1)	Lower Ant (F2)	Upper Ant (F1)	Lower Ant (F2)	Upper Ant (F1)	Lower Ant (F2)
SOQPSK 5Mbps (Baseline)	**76.7%**	**86.2%**	**72.9%**	**80.5%**	**81.4%**	**81.5%**
SOQPSK 20Mbps (Baseline)	**73.0%**	**79.4%**	**75.2%**	**84.9%**	**84.3%**	**90.9%**

PCMFM with Frequency Diversity:

The numbers in table 5 illustrate Link Availability when frequency diversity is applied on a per receive site basis using PCMFM modulation. For this test, channel 1 of the telemetry receiver was tuned to the upper antenna frequency (2240.5MHz), channel 2 was tuned to the lower antenna frequency (2260.5MHz) and the receiver's internal maximal ratio combiner was used to select the best signal. Link Availability was calculated for this combined signal at each receive site.

Table 5 PCMFM Frequency Diversity Link Availability

	LINK AVAILABILITY		
	Site 4	Site 2	CM4
Flight	Combined	Combined	Combined
PCMFM 5Mbps	**99.3%**	**96.2%**	**97.0%**

SOQPSK with Frequency Diversity:

The numbers in table 6 show Link Availability when frequency diversity is applied on a per receive site basis using SOQPSK modulation. For this test, channel 1 of the telemetry receiver was tuned to the upper antenna frequency (2240.5MHz), channel 2 was tuned to the lower antenna frequency (2260.5MHz) and the receiver's internal maximal ratio combiner was used to select the best signal. Link Availability was calculated for the F1/F2 combined output at each site for both 5Mbps and 20Mbps.

Table 6 SOQPSK Frequency Diversity Link Availability

	LINK AVAILABILITY		
	Site 4	Site 2	CM4
Flight	Combined	Combined	Combined
SOQPSK 5Mbps	**97.0%**	**95.1%**	**92.4%**
SOQPSK 20Mbps	**95.3%**	**96.4%**	**97.5%**

PCMFM with Frequency and Spatial Diversity:

Building upon the results for frequency diversity, spatial diversity was then added to further increase LA. For this test, each channel (F1/F2) of each receiver at each site (3 sites), totaling 6 telemetry streams, was assigned a DQM value and sent via the DQE message to the Best Source Selector. The BSS then made bit-by-bit source selection based upon the DQM value of each input

stream. This combined stream was then sent to the BERT. Link Availability of this BSS-combined link is shown in table 7.

Table 7 PCMFM Frequency/Spatial Diversity Link Availability

	LINK AVAILABILITY
Flight	Best Source Selector
PCMFM 5Mbps	**99.4%**

SOQPSK with Frequency and Spatial Diversity:

This test configuration is the same as the previous section (PCMFM with Frequency and Spatial Diversity) but with SOQPSK modulation at 5Mbps and 20Mbps. Link Availability of this BSS-combined link is shown in table 8.

Table 8 SOQPSK Frequency/Spatial Diversity Link Availability

	LINK AVAILABILITY
Flight	Best Source Selector
SOQPSK 5Mbps	**96.7%**
SOQPSK 20Mbps	**97.3%**

SOQPSK with STC and LDPC:

This test combined SOQPSK modulation with STC and LDPC. Because frequency diversity was no longer used, the single frequency transmitted was 2240.5MHz with one RF port of the transmitter connected to the upper antenna and the other RF port connected to the lower antenna. STC is being used to mitigate the self-imposed "two antenna problem" (previously mitigated with frequency diversity) and LDPC is being used to correct errors caused by the transmission channel. Each receive site coupled the telemetry receiver, CH1 and CH2, to both receive polarizations, left hand circular polarization and right hand circular polarization. (Note: Polarization diversity combining, a normal practice on every test range, was not employed as individual polarization link availability numbers were measured). LA numbers at each site for each receive polarization are presented in table 9.

Table 9 SOQPSK STC/LDPC Link Availability

	LINK AVAILABILITY					
	Site 4		**Site 2**		**CM4**	
Flight	LHCP	RHCP	LHCP	RHCP	LHCP	RHCP
SOQPSK STC/LDPC 5Mbps	**96.3%**	**97.5%**	**95.9%**	**96.7%**	**97.1%**	**96.2%**

SOQPSK with STC/LDPC and Spatial Diversity:

This final test combined the STC/LDPC configuration with spatial diversity and best source selection. Each polarization (RHCP/LHCP) from each receiver at each receive site (CM4/Site 2/Site 4), totaling 6 telemetry streams, was assigned a DQM value and sent via DQE to the Best

Source Selector. The BSS performed its function on these six sources and sent the selected output to the BERT. Link Availability of the output of the BSS was calculated and shown in table 10.

Table 10 SOQPSK STC/LDPC Spatial Diversity Link Availability

	LINK AVAILABILITY
Flight	Best Source Selector
SOQPSK STC/LDPC 5Mbps	**100.0%**

Test Data Analysis:

There are multiple ways to analyze the volume of data that was collected during the flight testing. The point of this paper is to highlight the systematic gains in Link Availability that are possible given the various mitigation techniques available today. In addition to this, and perhaps more importantly, an emphasis should be placed on the importance of assessing link quality at the telemetry receiver, i.e., the Data Quality Metric, and providing that information via Data Quality Encapsulation to a Best Source Selector to intelligently select the best data and provide that to the end user.

Modulation Comparison.

Before mitigation techniques are analyzed, a quick comparison of modulation schemes, both operating at 5Mbps, shows PCMFM as the clear winner for a helicopter operating in this transmission channel. This should be of no surprise as historically PCMFM is known as a very robust waveform with extremely fast receiver resynchronization properties, there is a reason it was used for over 40 years to telemeter data. Conversely, it is not nearly as spectrally efficient as SOQPSK. With three modulation schemes to choose from today, the trade-off when selecting one is spectral efficiency (bits/sec/Hz) versus Link Availability.

Another conclusion from the data presented in table 11 is that the bottom antenna provided better LA. This was due in part to the flight profile and to the proximity of the rotary wing to the top transmit antenna. The flight profile caused portions of the flight where the upper antenna was shadowed from the receive site antenna due to the helicopter airframe. The proximity to the rotary wing amplitude modulated the telemetry signal that at times caused the receiver to lose synchronization. Both conditions adversely affected overall Link Availability.

Table 11 – Comparison of Modulation Scheme Link Availability

	LINK AVAILABILITY					
	Site 4		**Site 2**		**CM4**	
Flight	Upper Ant (F1)	Lower Ant (F2)	Upper Ant (F1)	Lower Ant (F2)	Upper Ant (F1)	Lower Ant (F2)
PCMFM 5Mbps (Baseline)	**86.1%**	**93.6%**	**77.0%**	**87.0%**	**83.3%**	**90.1%**
SOQPSK 5Mbps (Baseline)	**76.7%**	**86.2%**	**72.9%**	**80.5%**	**81.4%**	**81.5%**

Mitigation Technique Comparison with PCMFM Modulation.

Investigating systematic gains in LA for PCMFM came next. Space-Time Coding or LDPC forward error correction was not implemented, only frequency and spatial diversity techniques for

the link operating at 5Mbps. LA for each receive site and for each transmission frequency is presented as a baseline. Consider each one of the baseline LA numbers in Table 12 to stand alone, in other words if data was being sent from the helicopter in a "normal" test, the data would be sent using one antenna at one center frequency and would be received using any of the three receive sites. Note, after reviewing the baseline LA tallies in table 12, using the bottom antenna would clearly be the best choice to support an actual test mission.

Table 12 – Comparison of Mitigation Techniques for PCMFM

	LINK AVAILABILITY					
	Site 4		Site 2		CM4	
Flight	Upper Ant (F1)	Lower Ant (F2)	Upper Ant (F1)	Lower Ant (F2)	Upper Ant (F1)	Lower Ant (F2)
PCMFM 5Mbps (Baseline)	**86.1%**	**93.6%**	**77.0%**	**87.0%**	**83.3%**	**90.1%**
PCMFM 5Mbps (Freq Diversity)	**99.3%**		**96.2%**		**97.0%**	
PCMFM 5Mbps (Freq/Spatial BSS)	**99.4%**					

Frequency diversity was the first mitigation technique explored. Each receive site configured the telemetry receiver to IF combine (IF combining) F1 and F2 and output the combined demodulated signal (data and clock to the BERT) where LA tallies were then calculated. IF combining, typically polarization combining and not frequency combing, is done every day on every test range. In this case, significant gains in LA were achieved using this technique, at Site 4 LA increased from 93.6% to 99.3%.

The culmination of mitigation techniques for PCMFM resulted in a combination of frequency and spatial diversity. For this test, the IF combiner in the receivers at each site was not used rather each channel in the telemetry receiver (CH1 for F1, CH2 for F2) from each receive site was assigned a data quality metric and then sent via the range infrastructure using data quality encapsulation to the BSS giving it 6 sources, with a quality estimate for each source, in which to choose between. In this configuration resulting LA was 99.4%. In comparison, telemetry reception implemented in a fashion very similar to standard range practices today resulted in a best LA of 93.6% (single frequency, bottom antenna, Site 4). Coupling diversity techniques led to a very impressive gain in LA. Realize this gain was achieved without the use of advanced techniques like Space-Time Coding, LDPC forward error correction, or equalization, rather tried and true diversity techniques made possible today with a link quality assessment made at the receive site, DQM.

Mitigation Technique Comparison for SOQPSK Modulation.

Progressive use of mitigation techniques available for SOQPSK modulation at 5Mbps were applied to the telemetry link with the goal of systematically increasing LA. Baseline LA numbers were calculated for each transmit antenna, transmission frequency, and receive site. These baseline numbers can be considered as typical link performance numbers, the configuration is representative of how a standard flight test would transmit and receive data. Once again, if only using one transmit antenna was the choice using the bottom antenna would clearly be the best choice. Best LA was 86.2% using the bottom antenna and receiving that signal at Site 4.

Frequency diversity was tried next and measured on a per site basis (Site 4/Site 2/CM4). This was achieved by configuring the telemetry receiver at each site to IF combine the two frequencies (F1, F2) transmitted from the helicopter and output the demodulated combined signal. LA was

calculated for this output and shown in Table 13, the highest LA was 97% achieved at Site 4. Note: IF combining signals is not a new concept as most test ranges implement polarization diversity, using the left-hand and right-hand polarization from the receive antenna as the diverse sources rather than F1 and F2.

Spatial diversity was then added using each received signal from each receive site (F1 and F2 with no IF combining) resulting in 6 frequency/spatially diverse signals which allowed the BSS to choose the best information. This configuration combining frequency and spatial diversity resulted in a LA of 96.7%. This result is slightly worse than the result obtained using only frequency diversity with single site reception. After reviewing the data, this was caused by an inconsistent start time when calculating LA for both cases. For the purpose of this paper those LA numbers can be considered equal.

Applying advanced mitigation techniques was the final step towards trying to achieve error-free telemetry. The first step towards this goal was to determine single site link performance by coupling Space-Time Coding and Low Density Parity Check forward error correction to the telemetry link. Each site used LHCP and RHCP as CH1 and CH2 inputs to the telemetry receiver and LA was calculated for each of these. Best LA that was achieved for this configuration was 97.1% receiving LHCP at CM4. Note, this single site LA is greater than what was achieved using frequency and spatial diversity with uncoded SOQPSK.

Lastly, using the STC/LDPC configuration with best source selection was tried. The received signals (STC/LDPC RHCP, STC/LDPC LHCP) had a data quality metric assigned to each signal. This was done at each of the three receive sites then each was encapsulated for transfer to the best source selector located at Site 4. As with previous tests, this gave the BSS 6 diverse sources in which to make a bit by bit link selection based upon the assigned DQM for each source.

It is important to understand this last configuration for both the airborne platform and ground stations prior to taking an in-depth look at the results. The STC-enabled transmitter had one RF output (S0) connected to the top antenna, the other RF output (S1) connected to the lower antenna and both STC and LDPC were enabled in the transmitter. Data was PRBS23 at a rate of 5Mbps (uncoded), over the air rate after applying STC and LDPC was 7.8125Mbps which was transmitted at a frequency of 2240.5MHz. At each receive site the telemetry receiver had CH1 connected to the LHCP RF multicoupler, CH2 was connected to the RHCP RF multicoupler, and STC and LDPC decoding for SOQPSK was selected for each channel. The receiver then applied a DQM value to each signal and encapsulated that information (see figure 6) for transmission via TMoIP to the best source selector located at Site 4. A total of 6 diverse sources were applied to the BSS which first time correlated the sources then made bit by bit link selection based upon the assigned DQM. The output of the BSS was connecter to a bit error rate tester where bit error statics were displayed and logged.

The flight path shown in Figure 5 was flown and bit error statistics were captured throughout the flight. Referring to table 13, LA for this flight and test configuration was **100%**. Equation 1 for link availability tells us this result means there were no severely errored seconds (SES) and no pattern loss seconds (PLS) throughout the flight. Further investigation of the recorded bit error statistics revealed that the output of the BSS had zero bit errors throughout the flight. This configuration delivered the desired result, error-free telemetry.

Table 13 – Comparison of Mitigation Techniques for SOQPSK

	LINK AVAILABILITY					
	Site 4		Site 2		CM4	
Flight	Upper Ant (F1)	Lower Ant (F2)	Upper Ant (F1)	Lower Ant (F2)	Upper Ant (F1)	Lower Ant (F2)
SOQPSK 5Mbps (Baseline)	**76.7%**	**86.2%**	**72.9%**	**80.5%**	**81.4%**	**81.5%**
SOQPSK 5Mbps (Freq Diversity)	**97.0%**		**95.1%**		**92.4%**	
SOQPSK 5Mbps (Freq/Spatial BSS)	**96.7%**					
	LHCP	RHCP	LHCP	RHCP	LHCP	RHCP
SOQPSK STC/LDPC 5Mbps	**96.3%**	**97.5%**	**95.9%**	**96.7%**	**97.1%**	**96.2%**
SOQPSK STC/LDPC 5Mbps (Spatial/BSS)	**100.0%**					

Further investigation of this revolutionary result is justified. The underlying assumption of utilizing diversity for telemetry systems is that the channel distortion is uncorrelated with respect to the diversity method. For example, if diversity is used it is assumed that channel distortion including multipath, composite transmission antenna pattern nulling, ground station antenna pointing error, or threshold signal-to-noise ratio (SNR) do not happen at the same time at each receive station. For this test, this can be shown to be true by plotting the estimated signal quality/bit error probability that each receiver assigned the signal throughout the test. This information was captured at each receiver and then again at the BSS, see figure 6. If the above assumption is correct, there should be no correlation of the channel distortion between receive site/receive polarization.

Figures 7 and 8 show a plot of the estimated BEP (DQM) of each of the 6 received signals during the entire flight. Figure 7 groups the estimated BEP for LHCP from the three receive sites and Figure 8 groups estimated BEP for RHCP. If the distortion was time correlated these plots would show groupings of estimated BEP indicating that errors occurred at exactly the same time. If the plots were overlaid and magnified, the resulting plot would show that there were groupings on a per site basis where degraded BEP was time correlated but when analyzed between the three sites there was no time correlation of the events. Degraded BEP, errors that could not be corrected by coding, occurred at different times between the three receive sites. Ultimately we know this to be true as the BSS ALWAYS had an error-free source to select.

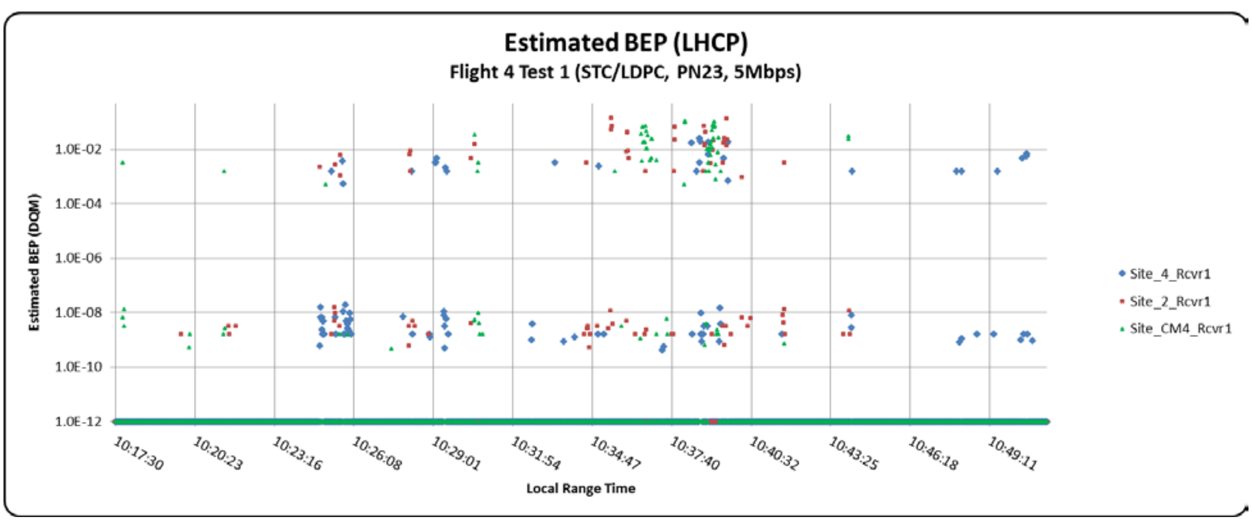

Figure 7 – Estimated Bit Error Probability, LHCP

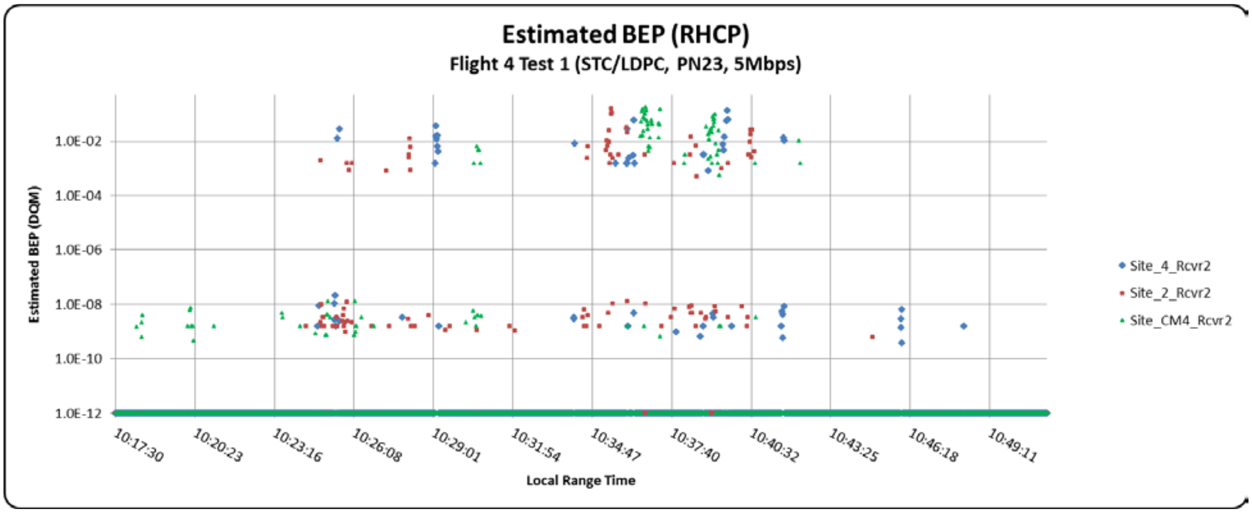

Figure 8 – Estimated Bit Error Probability, RHCP

Implementation:

If diversity techniques are to be employed at a given range, several questions must be asked and answered prior to implementation. First off, what type of diversity is going to be employed? Both frequency and spatial diversity with DQM/DQE enabled best source selection were shown to provide significant gains in LA. A combination of the two showed even more gain. Does the range possess enough of the needed commodity to employ the selected diversity technique? For frequency diversity, is there enough AMT spectrum to transmit the same information on two different frequencies, doubling the spectral occupancy? For spatial diversity, are there multiple receive stations that can be dedicated to one test article?

If it is determined that diversity is a viable solution, there are implementation requirements and associated costs tied to the selected technique(s). These requirements and costs can be broken into two areas, those associated with the airborne test asset and those associated with the range infrastructure.

Airborne Test Article.

The test article must have a telemetry transmitter with optional Space-Time Coding and Low Density Parity Check for error correction and be configured for the intended telemetry band of operation. Coupled to the transmitter, two transmit antennas are required to provide a transmit capability for each RF port of the transmitter. An STC-enabled transmitter is really two separate transmitters that share a common baseband interface so this transmitter also allows for frequency diversity should that form of diversity be chosen over Space-Time Coding. A transmitter specified in this configuration costs between $30K-$45K.

Range Infrastructure.

The burden of implementing diversity falls mainly upon the ground station. The key technologies required are telemetry receivers located at each receive site capable of estimating and assigning a real-time data quality metric and a best source selector with the ability to time-align

multiple telemetry sources, interpret the DQE/DQM [10], and make bit-by-bit decisions as to the proper data stream to use as the best source. The receiver also needs the ability to capture and demodulate the space-time coded and LDPC coded signals should the test platform choose to implement them. A typical cost for a telemetry receiver with the options discussed above is ~$75K. Depending upon the receive strategy employed by the range, each antenna being used for diversity reception could need one to four receivers each. The best source selector will cost $50K but will typically be required for every control room capable of taking in multiple telemetry sources.

Along with this, and perhaps just as important, is the ability to provide spatially and/or frequency diverse signals in which to feed the BSS. Spatial diversity requires at least two telemetry receive antennas be dedicated to the mission. Frequency diversity requires twice as much bandwidth be scheduled for that test mission. A combination of the two diversity techniques requires both. Once the signals are received, demodulated, and a DQM estimate is assigned to each source, the range infrastructure must support low latency transmission of the DQE packets to the BSS. Also consider that the multiple sources may not come from only one range.

CONCLUSION

There are few transmission channels as challenging as the helicopter telemetry channel, flying at low altitudes coupled with rotary wing effects on the transmitted signal led to a multipath rich environment causing Link Availability as low as 76.7%. By coupling various mitigation techniques together for both PCMFM and SOQPSK modulation schemes, significant increases in link availability was achieved when compared to transmission and reception methods used today. These gains in LA were achieved using tried and true diversity methods as well as two AMT-specific technologies, Space-Time Coding and Low Density Parity Check forward error correction coding. The key enabling technology was the ability of the telemetry receiver to accurately estimate signal quality, an estimate of bit error probability, and pass that link quality information along to a best source selector with the ability to time align the sources and use the link quality estimate to <u>intelligently</u> select the best source on a bit-by-bit basis.

Both frequency and spatial diversity were shown to increase link availability significantly. Advanced mitigations methods, STC and LDPC also showed significant improvements in link availability. Ultimately, the combination of SOQPSK modulation and STC and LDPC with DQM/DQE assigned to the received signals allowed the use of a BSS to intelligently choose the best telemetry signal to output. This configuration achieved a LA of <u>100%</u>. Further investigation into this result led to the realization that not one bit error occurred at the BSS output, this is the definition of **error-free telemetry**.

Though the testing was performed in a severely impaired transmission channel, further testing using these multipath mitigation techniques should be conducted in other transmission channels. The logical next step would be to perform like testing in the fixed wing environment in both the over the land channel and over the water channel as both exhibit differing multipath profiles. As was the case in the helicopter environment, it is expected that gains in LA will again be observed utilizing diversity coupled with DQM/DQE enabled best source selection.

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First and foremost, YPG and the test staff including Mike Diehl, Tab Wilcox, and Jason Swain should be congratulated for not only allowing this telemetry experiment to be conducted on their range with their test assets, but also for having the forethought to request assistance from experts in the field of aeronautical telemetry and allow them the latititde to push the envelope of telemetry experimentation. Mark Geoghegan and Bob Schumacher from Quasonix should be acknowledged as subject matter experts, their years of AMT expertise was put to good use throughout the flight testing. Lastly, without the support of Tim Chalfant, the Air Force Test Center would not have been a major contributor in the test.

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APPENDIX A - ABBREVIATIONS, ACRONYMS AND SYMBOLS

Abbreviation	Definition
AMT	aeronautical mobile telemetry
ARTM CPM	Advanced Range Telemetry Continuous Phase Modulation
BEP	bit error probability
BER	bit error rate
BERT	bit error rate tester
bps	bits per second
BSS	best source selector
dB	decibel
dBm	decibel referenced to 1 milliwatt
DQE	Data Quality Encapsulation
DQM	Data Quality Metric
Eb/No	energy per bit to noise ratio
FEC	forward error correction
Hz	Hertz
IF	intermediate frequency
IP	Internet protocol
kHz	kilohertz
LA	link availability
LDPC	low density parity check
LHCP	left hand circular polarization
LR	log likelihood ratio
Mbps	megabits per second
MHz	megahertz
PCMFM	Pulse Code Modulation Frequency Modulation
PRBS	pseudo-random bit sequence
RHCP	right hand circualr polarization
RSSI	received signal strength indicator
SOQPSK	Shaped Offset Quadrature Phase Shift Keying
STC	Space-Time Coding
TMoIP	Telemetry over Internet Protocol
YPG	Yuma Proving Ground
%	percent

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